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16. ABSTRACT

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Most Traffic Departments among their responsibilities: (1) review proposed geometrics for new highway projects prepared by Design Departments; (2) Evaluate existing deficiencies and develop projects to alleviate these deficiencies.

Both of these objectives are impossible without a good understanding of capacity.

This discussion is intended to familiarize the reader with traffic flow characteristics. It does not contain a great amount of detail and for a more complete working knowledge of traffic flow, the above mentioned Capacity Manual should be studied. Traffic Bulletin #4 issued by the Division of Highways is also a good reference.

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DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

G. L. RUSSELL, Traffic Engineer

TRAFFIC BULLETIN NO. 16

INTRODUCTION TO CAPACITY

April, 1969

Prepared By:

Leonard Newman

INTRODUCTION TO CAPACITY

GENERAL DISCUSSION

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Definitions

Before discussing specifics, there are several concepts that should be understood. Some important definitions (from the 1965 Capacity Manual) are listed.

Capacity - "Capacity is the maximum number of vehicles which has a reasonable expectation of passing over a given section of a lane or a roadway in one direction (or in both directions for a two-lane or a three-lane highway) during a given time period under prevailing roadway and traffic conditions."*

There are several important points in this definition.

Capacity is not a single number. It is different for every section of road. And it is even different on one section of road under different conditions (e.g., under conditions of rain, ice, etc.).

Capacity is not a number of vehicles in an hour as is often supposed. There is no one time base in the definition. Capacity is a flow rate (usually expressed in terms of vehicles-per-hour) that a section can accommodate. As an example, assume that capacity of a particular lane under prevailing conditions is 1800 vehicles per hour (this is a rate). Also assume that the number of vehicles wanting to use the road the first 15 minutes is 350; the second 15 minutes is 450; the third 15 minutes is 550; and the fourth 15-minute period

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* Emphasis added.

is 400; a total for the hour of 1750 vehicles. The assumption that this road is operating at less than capacity is not true. The fact is that during the third 15-minute period the number of vehicles that want to use the road (rate of 2200 vph) is greater than the capacity (rate of 1800 vph) and all the attendant effects of demand exceeding capacity (discussed later) will occur.

A "bottleneck" section is defined as such a section: A section of road where the amount of traffic wanting to use it exceeds its capacity.

Peak-Hour Factor (PHF) - This is a term which describes the peaking of traffic within an hour. It is the ratio of the peak hour volume to the highest maximum rate of flow during a given time period within that hour. In the example above, the PHF (for 15 minutes) would be $\frac{1750}{2200}$ or 0.8.

You will note that there is nothing in the definition of capacity that relates to quality of traffic flow or how traffic operates. The term "level of service" is meant to define operating conditions. Level of service is a qualitative measure of the effect of a number of factors, which include speed, travel time, traffic interruptions, freedom to maneuver, comfort, and many others.

In practice a specific level of service is defined in terms of particular limiting values of certain of these factors.

Generally, the factors used in determining level of service are operating speed and the v/c ratio. The latter term is the ratio of the traffic volume the road is expected to handle to the capacity of the same section of road.

There are six levels of service - A through F - and for each one, depending on the type of road we are considering, (street or freeway) there is a limiting operating speed and v/c ratio.

Again, to use an example level A is considered the highest quality service there is and for a 4-lane freeway (2 lanes in each direction) operating speeds must exceed 60 mph and the v/c ratio must be less than .35. Therefore, the design of the road must be such that (1) a 60 mph operating speed can be maintained and (2) assuming a capacity rate of 1800 vph, the 2-lane one-way volume cannot exceed 1260 vph or only 630 vph per lane $\left(\frac{630}{1800} = .35\right)$.

As a matter of interest, the Division criteria for a rural freeway is 1000 autos/hour per lane. This is basically the upper limit of level B.

TRAFFIC FLOW CHARACTERISTICS

1. Capacity (uninterrupted flow)

Capacity is determined by how close drivers are willing to follow one another. Individual headways (the time it takes two successive vehicles to pass a point) vary from 0.5 second up. In other words, in a very short interval of time and for a very few vehicles, the rate-of-flow in one lane or one file can be as much as 7200 vph. However, on the whole it is found that any 100 vehicles traveling through a significant distance, such as a quarter-mile or more, will not accept <u>average</u> headways of less than 1.8 seconds, which is a rate of flow of 2000 vph per lane. On multi-lane facilities, some of the drivers in the total stream will accept lesser headways than this and these drivers tend to drive in the left-hand or median lane. For example, lane volumes in the median lane on many freeways consistently reach 2200 vph. This does not mean, however, that all vehicles in the stream (on all lanes) are willing to accept such short headways.*

Roadways should not be designed for capacity rates of 2,000 vph per lane since it is not usually possible to

* Headway size is also subject to many other things in addition to the drivers willingness to drive at a certain headway. For example, if three vehicles are following each other at 2 second headways and the middle vehicle changes lanes, then two vehicles are following at a 4 second headway.

get these volumes without considerable stop-and-go driving (see below). Also, capacity is hard to estimate and very often it will be less than 2,000 vph per lane. A capacity of 1800 vph per lane can usually be depended on and a basic fact about freeway traffic flow is that average headways of less than 2 seconds should not occur except for very short periods.

In terms of continuous flow, capacities are reduced below 1800 vph in one lane only if outside influence cause the average headway to become greater than 2 seconds. (On freeways, this is rare although it does occur as drivers go past a scene of unusual interest, such as an accident where capacity in one lane can be as low as 1200-1600 vph.) However, on surface streets where lanes may be very narrow and where there may be considerable friction or potential interference from pedestrians and parked cars, drivers tend to follow at greater headways in anticipation of conflicts or sudden maneuvers. Under these conditions, capacity may be reduced to about 1500 vph per lane.

2. Capacity (interrupted flow)

Capacity per lane seldom is reduced to less than 1500-1800 vph unless there is an interruption to continuous flow. Interruptions usually take the form of an intersection. Capacity of a street is primarily determined by the proportion of time the traffic is interrupted at a key intersection. For example, a city street lane having a normal capacity of 1500 vph will have a capacity of 750 vph if, at an intersection, it is allowed to proceed only one-half the time (i.e., a signal time cycle lasting 1 minute with 30 seconds of green-yellow to each street).

3. Relation between capacity and delay

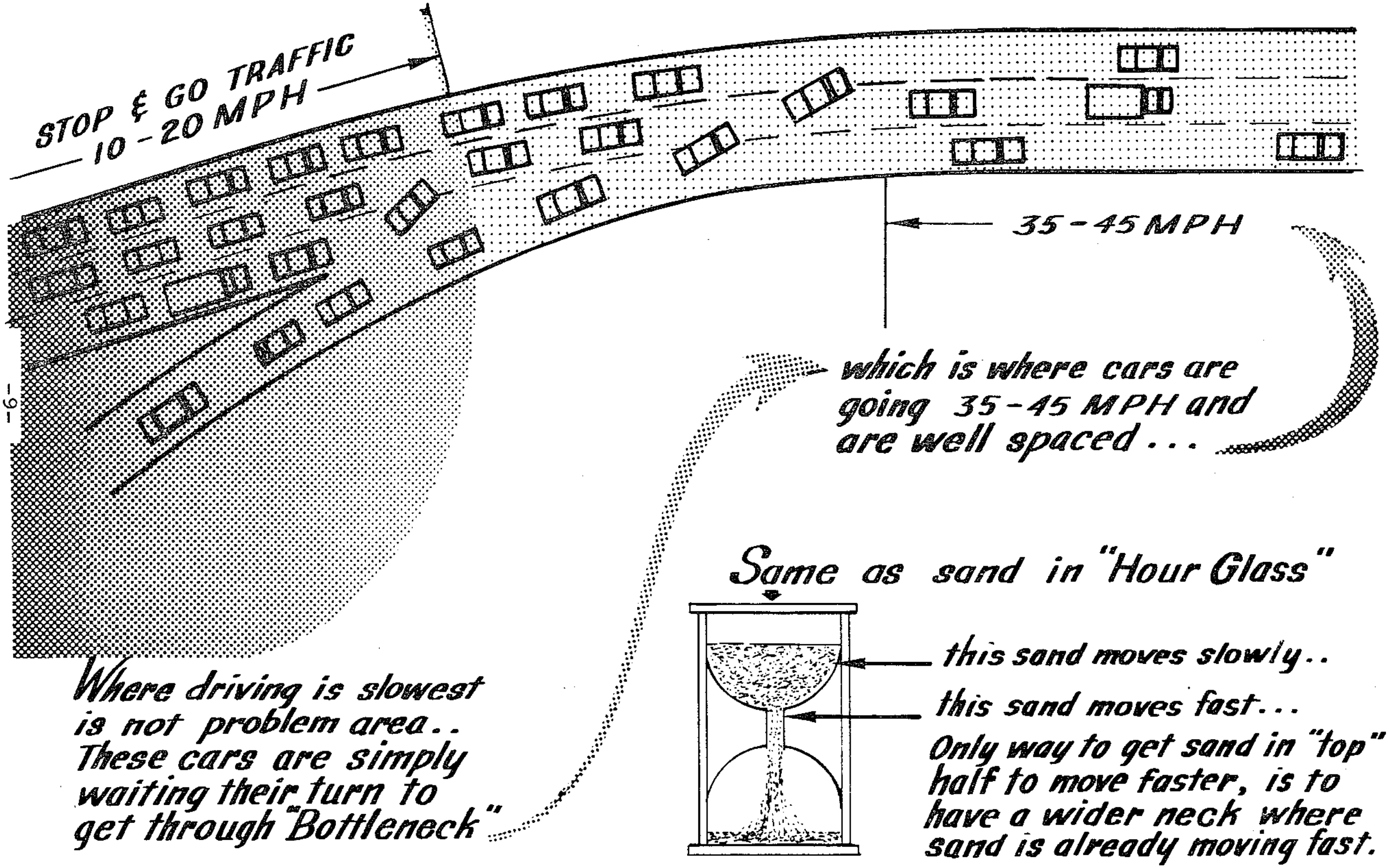
In terms of uninterrupted flow, average speed is reduced very little until volumes approach very near capacity.

On freeways or rural multi-lane highways, speed at very low volumes is simply what the motorists desire which in turn is determined by the character of the road, their own car, and the legal speed limit. If a vehicle overtakes a slower-moving vehicle, he can immediately pass without slackening speed. However, as volumes increase his opportunities to pass are reduced and his speed is then definitely influenced by speeds of other cars.

Speeds will still average over 50 mph even at average lane volumes of over 1500 vph. There is considerable driving tension under these conditions and even though there is little delay this type of operation is certainly not recommended for rural conditions where most drivers are on long trips (as opposed to shorter commuter type urban trips). Even at capacity volumes, speeds will still be in the 35-50 mph range and there will be little or no stop-and-go driving at the point where capacity volumes are being observed.

The severe delays taking the form of stop-and-go driving which occur on urban freeways and even on rural freeways are the result of "bottleneck" sections. The slow speeds are a <u>result</u> of a lack of capacity and is not a cause of problems as is so often stated. It is the same as sand in an hourglass. The neck of the hourglass can handle only so much sand and there is nothing the waiting sand can do about it. Roadway bottlenecks are the same thing. Each section has a particular capacity depending on many factors and if traffic demand exceeds this capacity, cars will have to wait. This waiting takes the form of stop-and-go driving. This is illustrated in the following sketch.

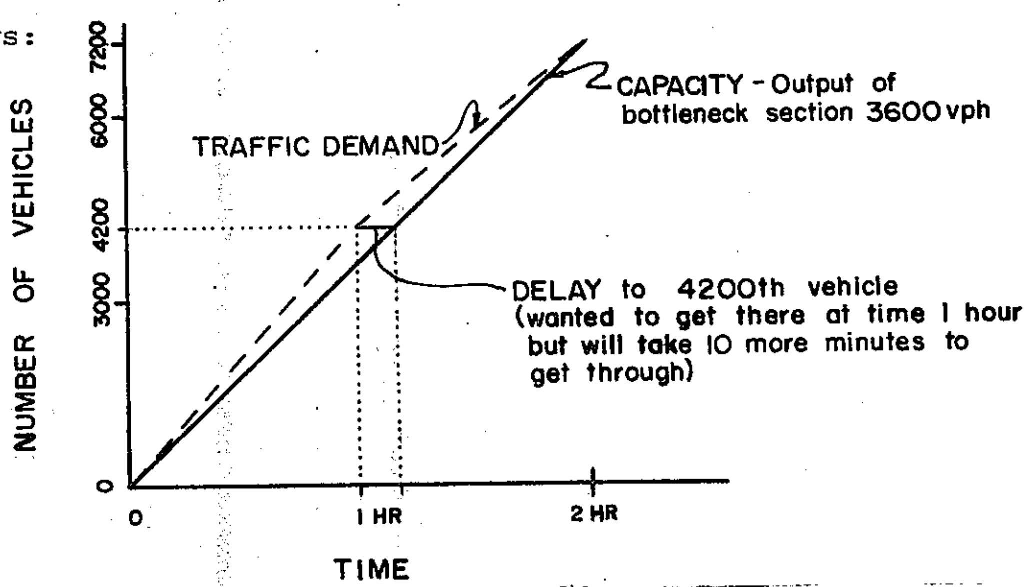
A Type of Freeway "BOTTLENECK"



This concept is very important and the following example illustrates this and shows why it is so important to avoid bottlenecks.

Assume a 2-mile section of road has a capacity of 3600 vph and for 2 hours cars arrive at exactly this rate. The average speed would probably be 45 mph and in terms of urban peak conditions we would not consider that there is any delay. In terms of rural conditions or motorists' desires (60 mph±), delay would be only 40 seconds for each vehicle.

However, from a practical point of view, traffic demand exactly matching capacity for one hour, much less two hours, rarely, if ever, occurs. Now assume that traffic demand the 1st hour is 4200 vph and 3000 vph the 2nd hour. Cars will immediately start to back up. At the end of the 1st hour 600 cars will be stored waiting to get through (and the 4200th car will be delayed 10 minutes--there are 600 cars ahead getting through at the rate of 3600 per hour--it will take him 1/6th of an hour). It will take another hour to dissipate the congestion and the average delay per vehicle will be 5 minutes. This is shown graphically as follows:

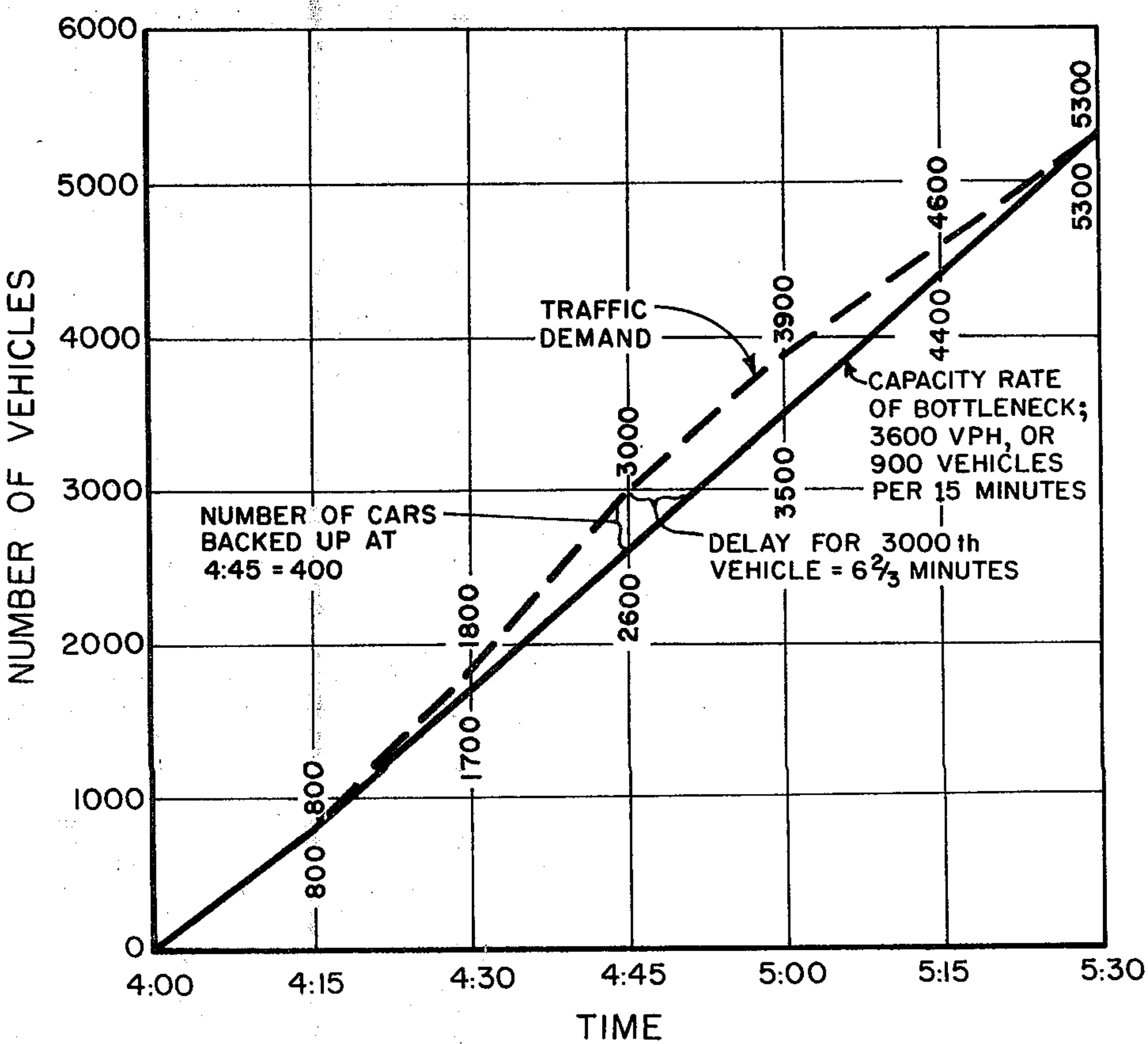


In order to emphasize the preceding principle, which is one of the most important things for a traffic analyst to understand, the following example is worked out in detail.

Assume a bottleneck section of freeway has a capacity of 3,600 vph. The following is the traffic demand from 4:00 to 5:30:

Time	Demand
4:00 - 4:15	800 vehicles
4:15 - 4:30	1000 vehicles
4:30 - 4:45	1200 vehicles
4:45 - 5:00	900 vehicles
5:00 - 5:15	700 vehicles
5:15 - 5:30	700 vehicles

Since the freeway has a capacity of 3600 vph, or 900 vehicles per 15 minutes, demand only exceeds capacity from 4:15 to 4:45 as shown above. However, the excess vehicles which arrive during this half hour must be temporarily stored until they can pass through the bottleneck and it is this temporary storage which causes the congestion to extend over a much longer time period. This is shown graphically as follows:


6000
5000
4000
3000
2000
1000
0
NUMBER OF VEHICLES
4:00
4:15
4:30
4:45
5:00
5:15
5:30
TIME
TRAFFIC
DEMAND
CAPACITY RATE
OF BOTTLENECK;
3600 VPH, OR
900 VEHICLES
PER 15 MINUTES
NUMBER OF CARS
BACKED UP AT
4:45 = 400
DELAY FOR 3000th
VEHICLE = 6 2/3 MINUTES
800
800
1800
1700
3000
2600
3900
3500
4600
4400
5300
5300

From this graph we can easily answer virtually any question concerning the bottleneck. For example, vehicles first begin to back up at 4:15 when 1000 vehicles per 15 minutes (4000 vph) want to enter the bottleneck but it can only accommodate 900 per 15 minutes. The back up of cars gets longer for a half hour until 4:45 because 2200 vehicles arrive in this half hour but only 1800 have been able to leave, and at 4:45 four hundred vehicles are waiting in line to enter the bottleneck. This 400 vehicles is the difference between the number which has arrived and the number which has been able to leave.

From 4:45 to 5:00, 900 more vehicles arrive but also 900 leave so the back up remains 400 vehicles. From 5:00 to 5:30 the back up gets shorter and finally disappears at 5:30 because only 1400 vehicles have arrived in this half hour but 1800 have been able to leave.

We can also determine delays from this graph. For example, the 800th vehicle arrived at 4:15 and suffered no delay due to the back up because the congestion was just beginning. However, the 3000th vehicle suffered a delay of 6-2/3 minutes because it arrived at 4:45 but had to wait its turn and could not leave until 4:51-2/3. This value can be found from the graph, or easily calculated from the fact that the 3000th vehicle is initially 400 cars back from the bottleneck and must wait while these 400 leave at the rate of 900 per 15 minutes ($\frac{400}{900} \times 15 = 6\text{-}2/3$ minutes). Total delay to all vehicles may be easily found by simply determining the area, in terms of vehicle-minutes, between the demand and capacity curves in the same way that a designer determines area of a cross section for earthwork purposes.

Another question that can be answered from this graph is what the true demand for the bottleneck is. This is done by "working the problem backwards", so to speak. In the above example, the demand was given. However, in real life it is often unknown. If we count the cars going through the bottleneck, we can plot the line labeled "capacity". By sending some floating cars through from upstream of the congestion, the delay can be determined at several time points (by subtracting normal travel time from actual travel time) and if these points are connected, they will determine the position of the "demand" curve. (Another, more accurate but more expensive way of doing it is to take aerial photos at several times during the peak period and count the cars "stored" upstream of the bottleneck.) Subtract from this the number of cars that would be in the same stretch of road at normal speed for the rate of flow at the bottleneck, and this gives you the locus of the demand curve measured vertically above the capacity (or output) line.

The important reason a person might want to know what the demand is, is to find out whether widening the road at a given location will solve a problem or merely shift it downstream to a bottleneck which does not now look like one because the first bottleneck is metering the input.

One other important point is that it is usually impossible to achieve capacity flow rates without some stop-and-go driving. Operation at capacity flow rates means that there are virtually no gaps or spaces in the traffic stream. Because of statistical variations in traffic, there has to be a reservoir of traffic somewhere to guarantee that all the spaces will be filled up. It is a rare case when traffic demand just equals capacity.

In terms of street operation, the relation between capacity and delay at bottlenecks (usually a major intersection) is the same. At less than capacity volumes, delays and average travel speeds are more a function of number of traffic interruptions, adequacy of signal system progressions, and other items of this nature (e.g., a given street with a given volume can operate at virtually any average speed from 10 mph to 30-40 mph).

INTERSECTIONS

One of the more important elements limiting, and often interrupting, the flow of traffic on a highway is the intersection at grade.

Although the volume of traffic that can reach and pass through an intersection may well be influenced by conditions remote from the intersection, the capacity of any specific intersection is determined largely by the effect of elements directly related to the approach roadway.

Among the most important are:

1. Physical and operating conditions such as width of approach (number of lanes), one-way or two-way operation, parking conditions.

2. Traffic characteristics such as turning movements, number of trucks and buses, pedestrian conflicts.

3. Control measures such as signals.

These factors are discussed in detail in the Capacity Manual and charts are included for calculating capacity and level of service provided at intersections based on these factors.

Any intersection which would tend to cause serious delay would also be signalized. A basic unit used to determine the adequacy of a signalized approach is vehicles per hour of green-yellow. For a general and relatively quick analysis of a signalized intersection, each approach lane (if it is 11 feet or more in width) can be assumed to handle, for design purposes, 1200 vehicles per hour of green-yellow time.* This is true if each lane has no interference while it has the green signal indication (e.g., pedestrian conflicts, etc.) and is true even for a single lane turning lane (two abreast turning may not be as efficient).

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* Capacity of a lane at a signalized apprcach is actually 1500 (or even up to 1700) vehicles per hour of green. But this generally means cycles are loaded and there are long back-ups. Because of this and PHF considerations, a quick analysis should be based on 1200 vehicles per hour of green-yellow.

The following is an example of how this can be used:

Conditions: An intersection of 2 one-way streets. Street A is 3 lanes wide and has an hour volume of 2,400 vehicles and must receive two-thirds of the total time. Street B has a traffic demand of 600 vph.

Problem: How many lanes must Street B have so that traffic demand on this approach will not exceed its capacity.

Solution: Since Street B will have one-third of the total time, each lane will have a capacity of 400 vph (one-third hour of green-yellow x 1200 vehicles per hour of green). Therefore, two lanes must be provided.

TWO-LANE ROADS

One basic characteristic differentiates traffic operation on a two-lane road from multi-lane facilities. Overtaking and passing maneuvers must be made in the traffic lane normally occupied by opposing traffic.

Inasmuch as the maintenance of a desired speed requires passing maneuvers, the volume of traffic and the highway geometrics, which establish available passing sight distance, have a much more significant effect on operating speeds than is the case on multi-lane roads. Therefore, whenever service volumes are considered for two-lane roads, the corresponding range in available passing sight distance (1,500 feet or greater) must also be considered.

The effects of restricting passing sight distances, trucks, and grades are discussed in detail in the Capacity Manual. Suffice to say that these elements greatly reduce the volume that a road can handle at a given level of service or operating speed and have even greater relative effects than these same factors have on multi-lane facilities. Within level A, for example, operating speeds must be 60 mph or higher. Under ideal conditions with continuous passing sight distance available, a service volume of 400 passenger cars per hour, total for both directions, may be achieved. Approximately 75 percent of the desired passing maneuvers can be made with little or no delay, the main deterrent, of course, being vehicles traveling in the opposite direction.

It has been generally considered, for two-lane highways, (in the Capacity Manual) that distribution of traffic by lane has practically no effect on operating conditions. Therefore, the capacity and maximum volumes for given level of service are expressed in total vehicles per hour regardless of distribution of traffic by direction.

Capacity has been indicated as being 2000 vph (total in both directions).

While it is recommended that the reader understand the material in the Capacity Manual regarding two-lane roads, some of it is pretty theoretical. The following discussion, which was prepared in our Headquarters Traffic Department, gives the basic facts that are pertinent to know when solving State highway problems.

Observations have been made that indicate capacity of a two-lane rural highway is 1400 vph in either or both directions, provided that the distance between junctions where traffic can be added to the stream is less than about 5 miles. This means that for short stretches, if the demand is there, a two-lane road can handle 2800 vph--but, again, the demand is not likely to occur in this fashion. For practical purposes and because effects of length, sight distances and grades are not known very precisely, it can be assumed that the capacity of a two-lane road is about 1,000 cars per hour in the major direction with the possibility that up to 1200 can be accommodated with some queuing. This figure is useful to remember for short-range planning purposes so that the effect of a two-lane bottleneck during the long-range conversion of a two-lane road to a four-lane road can be anticipated. However, it is not very useful for design purposes on rural highways.

Generally, the only question that directly involves two-lane road capacity and needs answering by an engineer in the Division of Highways is: Shall we go to four lanes or will two be enough? It is really not very necessary to know much about what volume of traffic will create a certain "design level of service" or any other level of service on a two-lane road because within the foreseeable future (20 years) there will always be a backlog of two-lane highways on the State Highway System which requires conversion to four-lane highways.* On these roads the volume already exceeds the acceptable amount for a satisfactory level of service. For long-range planning purposes, the old rule of thumb of 5,000 cars per day in flat country is good enough. There are many examples, however, of mountain roads where the volume is between 3,000 and 5,000 cars per day which obviously should be converted to four-lane highways.

On the other hand, when it comes to widening two-lane roads in suburban areas, it should be remembered that between signals the capacity _is_ 1400 vph in one direction; the control on travel time or average journey speed in this type of situation is the capacity of the intersections and quality of service is a function of the signal timing at major intersections. _No signal should be installed on a two-lane road_. If the highway cannot be made at least four lanes prior to or simultaneously with signal installation, at least the intersection must be widened to provide for two abreast movement on the major legs. But remember that unless the

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* Incidentally, it might be mentioned that more than 80% of the travel on the California State Highway System is on roads of four lanes or wider.

one-way demand exceeds 1400 vph, changing a two-lane road that does not have signals on it into a four-lane city street will probably not either increase the journey speed nor decrease the accident rate. If it does neither of these things, justification for the project must be based on considerations that have nothing to do with capacity.

Some highways on the State Highway System are important routes by virtue of their function of connecting up various remote parts of the State but do not carry more than 1,000 to 2,000 vehicles per day and should be improved to high standard two-lane highways prior to the time that they will warrant four lanes. Generally the deficiency is caused by a combination of grades and poor passing sight distances. If the highway warrants improvement for reasons other than volume and it is decided that a 60 mph or better speed is to be provided, provision should be made in the initial grading for the paving of a climbing lane on any grade exceeding 2% and one mile in length or 4% and one-half mile. Not enough is known about the probability of passing opportunities to give any numerical values for volume per hour of passenger cars and trucks. It can be stated that whenever the highway gets important enough to require major construction to high standards, this climbing lane provision should be made, regardless of volume. On this type of highway, the justification for improvement is not based on volume, and any references to hourly capacity is meaningless.

For the purpose of providing climbing lanes, it should be acceptable to use what would normally be the shoulder for the climbing lane. That is to say, if the normal cross-section is 40 feet, meaning 20 feet each side of centerline in the flats, it is necessary to provide only 6 feet more or 26 feet to the right of centerline in the uphill direction. The area next to the hinge point can be used jointly by stalled vehicles and moving trucks because the purpose of either a shoulder or a climbing lane is only to reduce the probability of conflict, and since the probability of both kinds of conflict occurring at the same spot at the same time on any highway, which carries so little volume that it does not warrant four lanes, is already so low, there is no point trying to reduce it even further. Always remember that in any discussion of service levels or safety, we cannot do anything except work with probabilities. There is no such thing as providing zero probability of conflict.

RURAL FREEWAYS

On rural freeways, where most of the trips are long trips, the traffic volume during the design hour should be low enough to provide a reasonable degree of freedom of maneuver and absence of tension on the part of the drivers. This volume is quite low in comparison with the capacity of the freeway.

Even at extremely low volumes, there will be occasions where 3 cars driving at steady speeds on a two-lane one-way roadway will all reach a given point on the road at one time, and a certain amount adjustment of speed is required. The aggregate of such adjustments is negligible, in terms of psychological annoyance, up to the values discussed below. On grades, the aggregate or cumulative adjustments or conflicts are more frequent, but if the grades are short or if they are long distances apart, the cumulative tension for the trip is not increased very much. On the other hand, the capacity of any grade should never be exceeded.

On four-lane freeways (two lanes in each direction) it is found that at about 1400 vehicles per hour in one direction on a level grade, the faster group of drivers begin to be reluctant to use the right-hand lane for fear of being "trapped" in that lane behind slow vehicles while an entire platoon of "fast" vehicles passes the slow vehicle. When rates exceed this number this effect begins to be significant and the "trapped" vehicles will begin to break into the platoons passing in the left lane.

Curves showing speed versus traffic volume are not sensitive enough to pinpoint this effect. The faster platoons in the left lane are traveling 55-65 mph and the slow vehicles in the right lane are traveling 45-55 mph. The average speed of all vehicles is very slightly less than it is during low-volume flow. An observer standing at one location will note that long intervals go by between platoons, during which all cars are free moving, and then a platoon will go by in which the headways in the left lane are very short. It does not look like heavy flow, but about 50% of the drivers will be in a state of tension, driving "bumper-to-bumper".

When there are three or more lanes in one direction, the probability of being trapped in the slow lane is reduced to negligible proportions at hourly volumes of less than 1500 per added lane. It follows that for a given level of freedom, a freeway having three or more lanes in one direction will allow for a higher average hourly lane volume.

The following table may be used as a guide for determining the traffic volume which will result in practically unrestricted flow on various widths of freeway. Values are shown both for passenger cars only, and for a normal percentage of trucks or slow vehicles. This percentage rarely exceeds 5% during the peak hour.

Practically Unrestricted Flow on Level Grades.
(Very High Level of Service-Level B)
(Rural Long-Distance Freeways)

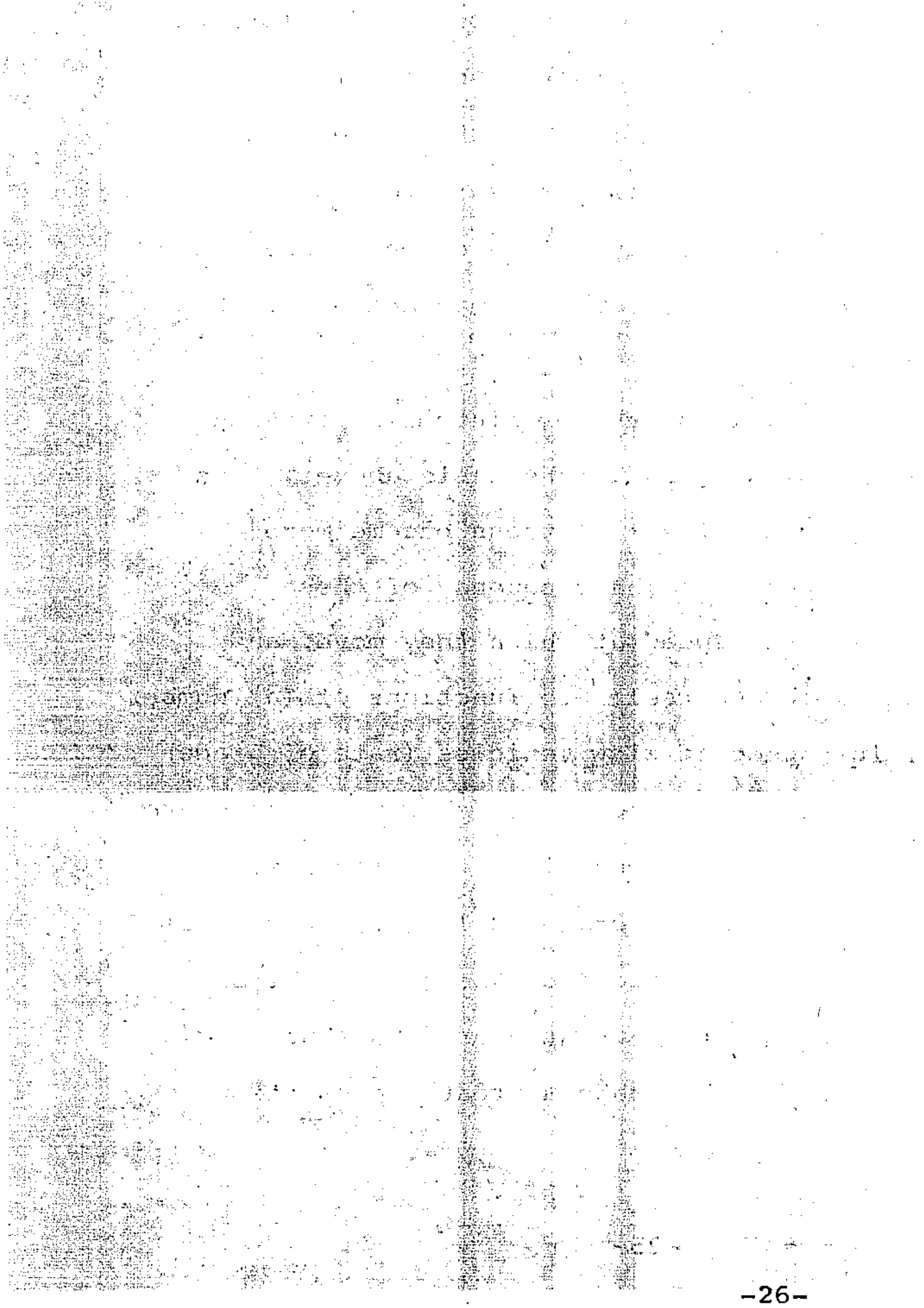
Number of lanes in direction	Hour Volume in One Direction	
	No Trucks	5% Trucks
2	2,000	1,700
3	3,500	3,000
4	5,000	4,400

The values shown are not capacity volume. The only reason for listing them is to evaluate a quality of flow that will be acceptable for long distance travel with almost complete absence of tension, and to show the effect of additional lanes for this quality of flow. This represents level of service B. It is not necessary to consider the PHF since volumes are so low and variability within the hour would not result in delays generally associated with capacity flows. What we are really after is a high probability of flow with little interaction between vehicles.

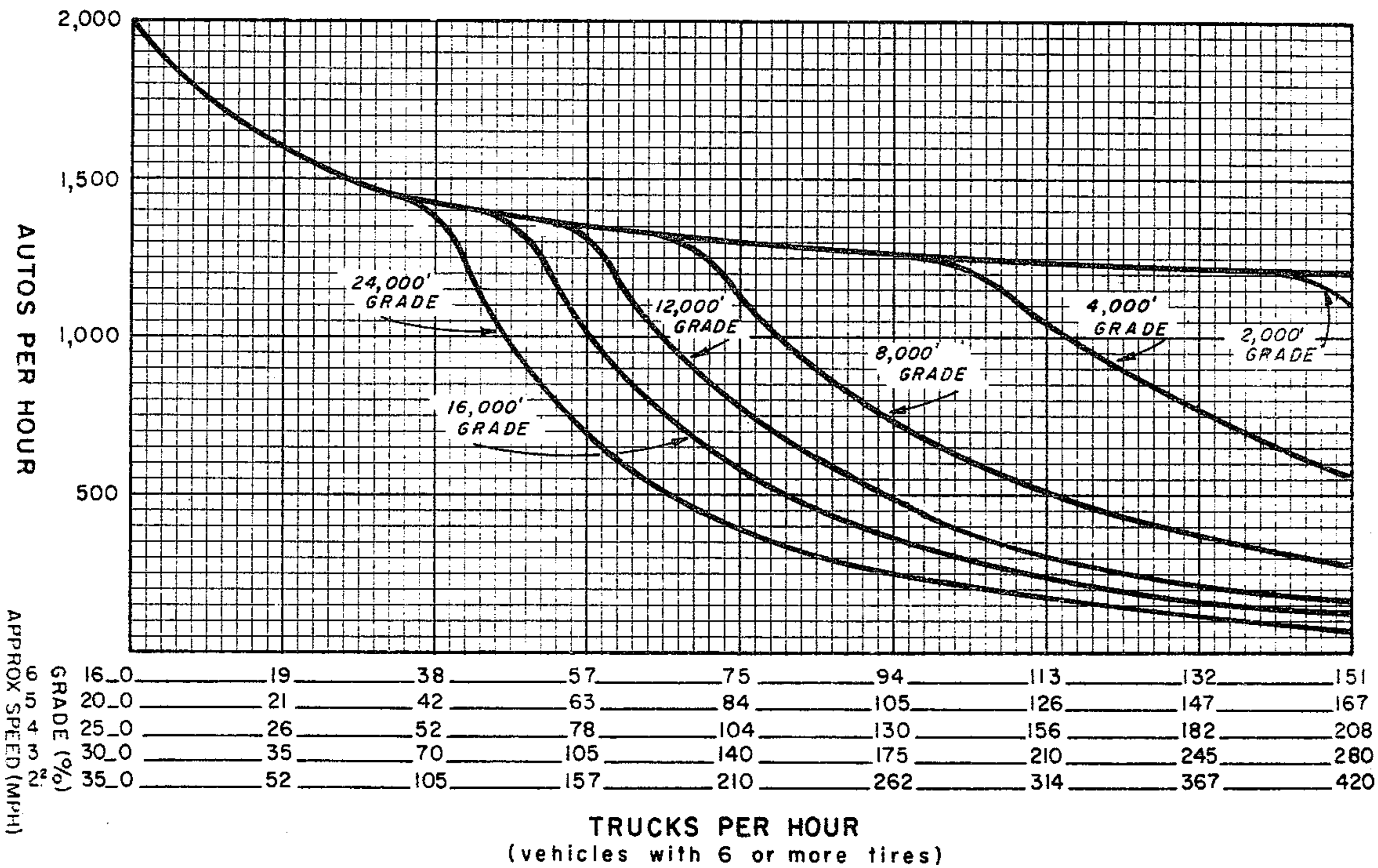
On sustained grades (more than one-half mile), the right lane will be pre-empted by trucks, and if it is desired to maintain a quality of flow on the grade equal to the quality on the level, it is necessary to add a climbing lane whenever the one-way volume exceeds 1000 vph. However, because of economic factors, it may not always be desirable to do this.

There is a certain amount of platooning even on level roads at the volumes shown in the table above. When a plus grade is introduced, these platoons become more serious controls on capacity. The frequency of these platoons or "bunches", the speed at which they move, and the capacity of the roadway itself are functions of (a) number of slow vehicles, (b) speed of slow vehicles (rate of grade) and (c) length of grade. If the grade is short and there are few trucks there is a certain probability that there will be no trucks on the grade. I f the grade is longer, there will be a greater probability that trucks on the grade will be encountered. Also, if the grade is steeper (and thus trucks slower), trucks will be on the grade a greater proportion of the time.

The following chart relates these effects for various grades and number of trucks. Any point on these curves would provide equivalent driving conditions - level of service B or the same as 1,000 autos per hour per lane on a level section with no trucks.



EQUIVALENT SERVICE VOLUMES RELATING TRUCKS, GRADES, AND AUTOS ON 2-LANE ONE-WAY ROADWAYS



URBAN FREEWAYS

The capacity of an urban freeway is no different than a rural freeway. The only difference is that in the urban situation we can tolerate some reduced quality of flow and we design for near capacity volumes. We try to design to eliminate the type of delay caused by traffic demands exceeding capacity of particular sections.

As noted while capacity may be 2,000 vph per lane, we should provide enough lanes so that the average lane volume will not exceed 1,800 vph even for short periods. Because of the PHF, this means that an hour volume of 1,500 vehicles could have periods within the hour where the rate-of-flow would be 1,800 vph. It is important that the peak rates not exceed this. The PHF will vary from about .75 (in a small city) to about .92 (in a very large city of over 1,000,000).

If the above criteria is met and there are no unusual conditions on the freeway, this will result in smooth, if somewhat restricted, flow at 35-50 mph and without stop-and-go driving.

Although this information is useful in determining the basic number of freeway lanes, it is not sufficient information to design an urban freeway. During the peak hours, operating conditions on urban freeways are a function of capacity of bottlenecks in the system which may or may not be dependent entirely on the number of lanes. In many locations a bottleneck will have a high lane capacity, but in others, bottlenecks can occur at lane volumes considerably less than what would ordinarily be considered capacity.

The problem is to define the location of bottlenecks and to provide adequate capacity at those locations.

Bottleneck locations which have less then normal capacity are in general caused by situations causing a poor distribution of traffic by lanes. In other words, more traffic wants to use a particular lane than it has room for while other lanes are not being fully utilized. These locations may be categorized as grade problems, where slow vehicles cause poor distribution of traffic among the lanes, and merging and weaving problems at interchanges.

<u>Grades</u> - Sustained grades of any slope (defined as a grade long enough and steep enough to reduce average truck speed to less than 35 mph) greatly reduce capacity. Since most urban freeways will operate near capacity as a general rule, an extra lane must be provided on all such grades or we will be building in a section with less capacity than its adjoining sections.

As implied, it is very important, in order to maintain capacity, that the right lane(s) carry a relatively high volume of traffic. Not only do grades (increasing the number of slow vehicles) prevent this, but long level sections without significant entering and exiting volumes also can. Generally, there are enough slow vehicles in a stream to cause many drivers to avoid the right lane. In fact under high volume conditions, the right lane is used primarily by slower moving vehicles and vehicles preparing to exit or having just entered. If there are no ramps, there is no reason for drivers to be in the right lane. There are examples of freeways with three lanes in one direction with ideal design standards, level, normal percentage of trucks, but with essentially no ramp traffic for several miles having a capacity of only 5000-5200 vph.

INTERCHANGES

When capacity is reduced or operation affected due to interchange operation, the opposite effect is the cause. That is, the right lanes become overloaded while the left lanes are not fully utilized.

The analysis of interchange capacity is essentially the analysis of conditions at/or approaching ramp terminals.

The rate-of-flow that an on- or off-ramp proper (turning roadway) can handle is about the same as a freeway lane or about 1,800 vph. Whether the ramp volume can be accommodated at the intersection with the surface street is a separate problem and should be analyzed as a regular street intersection problem.

When capacity is a consideration, any on-ramp roadway more than 1,000 feet long should be 2 lanes wide when it is funneled to 1 lane at the merge. This allows passing and breaking up of queues and large gaps, thus permitting a more even arrival rate at the freeway and at higher speeds.

On an off-ramp, the amount of 2-lane roadway (or wider) beyond the exit nose is dependent primarily on capacity requirements at the surface street connection and storage space required.

The freeway terminals of ramps should be of standard design. The standard entrance ramp must provide: (a) adequate merging distance for high speeds as well as low speeds at every ramp, (b) in combination with the approach ramp, adequate length for entering cars to accelerate from any turning speed, (c) adequate merging distance for low volumes as well as high volumes.

Freeway to freeway connections are essentially the same as ramps and can be analyzed in the same manner. The turning roadway may be of a higher standard to permit higher speeds, but the terminals would be the same. The connections would be different only if the exit or entrance volumes were so high as to require that a lane(s) be dropped or added to facilitate 2-lane (or wider) exits or entrances.

Two-lane ramp connections to the freeway are not generally used unless a lane is added or dropped as noted above, but in some cases they are desirable even when a lane is not added or dropped. This could be the case when the ramp and freeway peak occurs at different times. If two-lane entrance ramp terminals are used, a parallel lane should also be provided for a substantial distance, in addition to the standard ramp taper, so that a portion of the ramp traffic will have a chance to move to the left before the remainder has to merge. Conversely, 2-lane exit ramps require a parallel approach lane in order to provide room for traffic to move to the right in advance of the ramp. If this is not done a high volume off-ramp will result in overloading the right lane even if the exit is 2 lanes.

Merging operation will be smooth as long as total ramp and adjacent lane rate-of-flow does not exceed 1,800 vph, provided that the entrance ramp terminal is long enough and has a gradual taper.

Maximum combined flow-rates for a merge of a particular ramp and adjacent freeway lane have been observed as high as 2,000 and 2,200 vph. However, it is not recommended that this figure be anticipated in design procedures, since there are certain conditions of geometric design and traffic characteristics (which are difficult to predict or evaluate) that can prevent its attainment. 1,800 vph is a dependable figure and can be counted on under almost all circumstances, with normal truck percentages and grades of less than 3%.

Merging operation will vary considerably depending on the relative proportion of traffic on the ramp and adjacent lane. The smaller the number of ramp vehicles compared to adjacent lane vehicles (with the sum of the two being 1,800 vph), the better the merging operation. Entering ramp vehicles tend to move at slower speeds than freeway vehicles, and also often tend to arrive in platoons because of signal control and on single lane ramps because of queuing behind slow vehicles. Thus, they are not as well spaced as freeway traffic, which causes higher instantaneous merging flow than would occur if ramp traffic arrived randomly. This also means that in most instances, for example, two ramps of 400 vph each will operate better than one ramp with a rate-of-flow of 800 vph.

In any case, regardless of the relative volumes, a combined flow rate of 1,800 vph will result in satisfactory operation. Operating conditions when this criteria is met will be such that average speeds (over the entire length of the merging area) will be between 30 and 40 mph.

The procedure in analyzing the adequacy of a design is to make sure that no individual lane will have to carry a rate-of-flow greater than 1,800 vph at any point. In other words, first, and most important, enough lanes should be provided so that the average flow rate across all lanes does not exceed 1,800 vph and second, the lane distribution should be such that no individual lane will be overloaded.

Weaving problems (except for very short weaving lengths) are basically lane overloading problems. If weaving is a problem, it is almost always true that one or more of the weaving lanes is overloaded.

The basic problem in implementing this procedure is to know how traffic will distribute across the freeway lanes.

Traffic on a freeway at a point can be divided into three segments:

1. Through traffic.

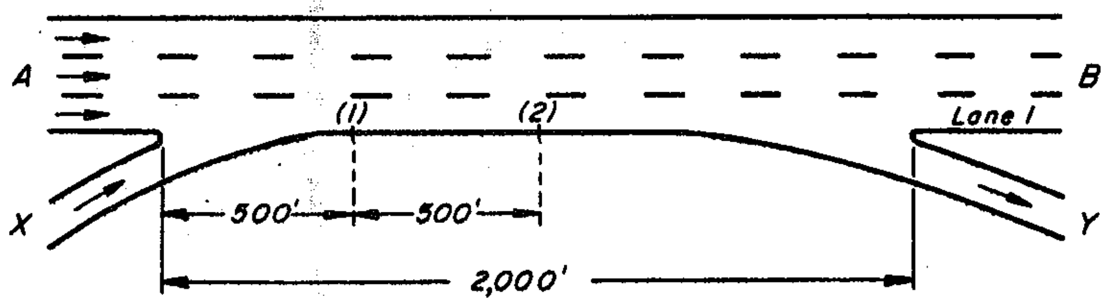
2. On-ramp traffic - traffic which has entered the freeway a certain distance upstream of the point or section under study. The entering point is considered the point where the left e.p. of the ramp lane is 2 feet from the freeway e.p.

3. Off-ramp traffic - traffic destined for an off-ramp a certain distance downstream of the point or section under study. The exiting point is considered the point where the left e.p. of the ramp lane is 12 feet from the freeway e.p.

The distribution of these segments by lane is described in detail in the Capacity Manual.

The following example illustrates the procedure that is suggested for checking adequacy at key locations where overloading might be suspected.

Example:



Given: (or assumed)

(a) 6-lane freeway

(b) on- and off-ramp 2,000 feet between noses

(c) Traffic data

A to B = 4,000 vph (highest rate within peak hour)

X to B = 700

A to Y = 600

X to Y = 0

Find lane volumes

(a) Average lane volume = 5300 ÷ 3 = 1,770

(b) Check right lane volume @ (1)

Thru traffic in right lane = 14%* x 4,000	=	560
On-ramp traffic in right lane 100%* x 700	=	700
Off-ramp traffic in right lane 79%* x 600	=	470
Total in right lane @ (1)	=	1730

(c) Check lane 1 volume @ (2)

Thru traffic in right lane	=	560
On-ramp traffic in right lane (.60 x 700)	=	420
Off-ramp traffic in right lane (.95 x 600)	=	570
		1550

Comments on the example:

It can be seen that the section would operate satisfactorily (lane volume rates are less than 1,800 vph) and the design would be acceptable since all conditions of the procedure are satisfied. However, a relatively small increase in the volumes or change in traffic patterns could change this

* Graphs indicating what these values should be under various conditions are contained in the 1965 Capacity Manual.

fact. It then becomes an economic question whether to build in an extra safety factor by adding an auxiliary lane on this which perhaps might be the most critical section of a freeway.